Composites: Part B 66 (2014) 147–155

Contents lists available at ScienceDirect

Composites: Part B

journal homepage: www.elsevier.com/locate/compositesb

Optimization of design parameters for Turkish Tirkeş (war) bow

Sermet Demir [a,*], Bülent Ekici [b]

[a] Department of Mechanical Engineering, Faculty of Engineering, Dogus University, 34722 Istanbul, Turkey
[b] Department of Mechanical Engineering, Faculty of Engineering, Marmara University, 34722 Istanbul, Turkey

ARTICLE INFO

Article history:
Received 19 October 2012
Received in revised form 31 January 2014
Accepted 28 April 2014
Available online 14 May 2014

Keywords:
A. Glass fibers
E. Lay-up (manual)
Parametric design

ABSTRACT

The bow and arrow is a projectile weapon system that predates recorded history and is common to most cultures. The Turkish bow is the most efficient one in its category. Despite of its superiority, Turkish bow is the one which is least documented in the literature. Technical drawings for the Turkish bow are missing. Turkish bow is a system consisting of different elements. Each element has its own distinctive feature and serves for a specific purpose. Recent interest in Turkish bow simply involves the replication of museum samples without any consideration about the performance characteristics of the replica.

The present work aims at describing the Turkish bow, war bow known as Tirkeş in specific. Characteristic shape parameters will be identified and the effect of each parameter on bow performance will be discussed. Parametric optimization to maximize bow efficiency will then be introduced. The bow shape will first be described. Characteristic shape parameters defining the bow geometry will be identified and the range in which they vary will be determined. The bow is drawn in the ANSYS® environment. Based on the design drawing a model bow is manufactured. Due to its superior flexing characteristics, E-glass fiber epoxy system is used in the composite structure. The model bow is tested to determine the characteristic draw weight – draw distance behavior of a typical bow. A mathematical model which is a simplified analysis of recurved bow types is used to compare behavior of model and manufactured bow draw weight – draw distance graph.

Using ANSYS, bow is optimized over the related domain. Only geometrical parameters are considered. Bow length, width and thickness are varied over their domain of definition and their effect on the bow performance is investigated. Limb part is taken as the working element and is optimized for high deflection and low weight. The optimization process results in response charts showing the effect of the design variables on output. Sensitivity analyses of the input parameters resulted in the influence weight of each parameter and how each parameter affects the output.

Using a goal-driven optimization approach, different design points were rate and the best design is identified. As compared to the effect of the other variable thickness is found to be the most influential variable affecting the draw weight.

1. Introduction

The bow with its arrow has been an efficient weapon in the past and it dates back to prehistory. Archery is the practice or skill of propelling arrow by using a bow. Historically, archery has been used for hunting and in combat, while in modern times, is practiced as an Olympic sport.

Turkish traditional archery goes back to the first millennium B.C. and is typical Scythians, Huns and other early Asian nations. The horseback archers of central Asian steps have used very similar archery tackling and fighting strategies throughout the entire history and the nomadic life style avoids making a clear, distinctive categorization of the tribes and nations [1,2]. In central Asia the arrow and the bow, together with the sword were characteristic weapons in hunting as well as in fighting. While the sword was the only weapon in face to face combat, the bow and the arrow was the long range weapon.

The Turkish bow is a recurved bow and incorporates organic composites. Its distinctive shape and the composite system used in manufacturing are responsible for its excelling power. Its short length provided important advantages such as ease of use on horse for horseback archers.

Turkish bow incorporates animal horn on the side facing the archer and sinew on the back side with a wooden core in the middle. Fish glue is used in sandwiching these materials. Due to its

* Corresponding author. Tel.: +90 216 444 55 55.
E-mail address: sdemir@dogus.edu.tr (S. Demir).

http://dx.doi.org/10.1016/j.compositesb.2014.04.029
1359-8368/

inherent nature, this technique of manufacturing the bow takes very long time [2–4].

Although Turkish bow is one of the best neither its design nor its manufacturing technique is not documented in the literature. Bowyers relied heavily upon experience in the design and manufacturing the bow. Also the effect of each element of the bow on its performance is missing as well. Bow makers learned through oral transfer of knowhow and trial (practical demonstration). A wide range of studies were made by Kooi [5–7], covering both the mechanics and the design of the bow. His works cover longbows and to some extent the recurved bows without any specific consideration of Turkish Tirkeş bows. Due to the lack of accumulated knowledge bow design and performance were improved by “try and cut” method [8]. The main goal of present work is to develop a working drawing of a typical Turkish bow based on museum samples, replicate a bow and test it, identify the basic parameters affecting the bow performance and through parametric optimization design a bow with maximum efficiency.

This paper deals with the geometry and the mechanics of the bow. Parts of the bow are clearly identified [9]. The length, thickness, width and profile of each part of bow are determined based on the traditional samples existing among museum collections. These parameters are taken as optimization parameters [4–10]. The dynamics of system are considered in global sense, which means that no discretization in time domain is necessary. Maximum elastic energy storage capacity per unit mass is calculated [11,12]. The influence of geometric parameters on the bow performance is separately calculated. While organic materials are used in the traditional Turkish bow, the bow studied in the present work involves synthetic materials which are E-glass fiber and epoxy. This preserves the composite structure of the original bow without affecting the optimization process.

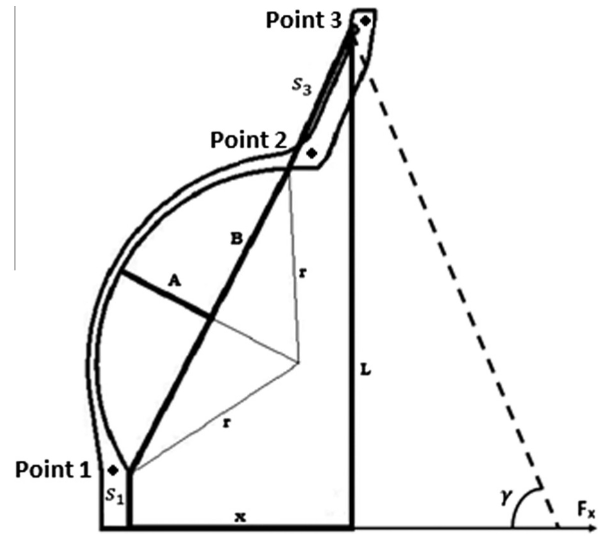

Fig. 2. Geometry of the drawn recurved bow (half part) [15].

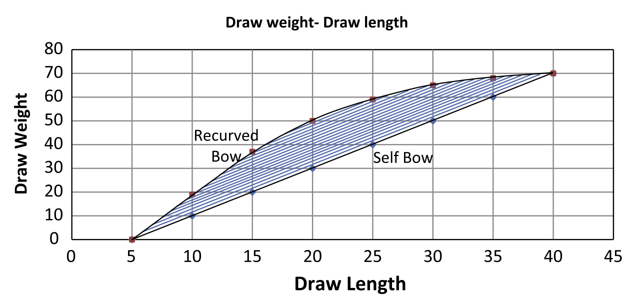

Fig. 3. The difference between recurved and self bow stored energy.

1.1. Description of the geometry

Turkish bow can be classified into three groups: war (Tirkeş), target (Puta) and long range (Menzil) bows. They are made of same material and at unstrung position they look like very similar to each other. Their differences appear at draw characteristics. The general composite bow states are illustrated in Fig. 1. Each part of a Turkish bow has its own name. Some of them have English equivalents but some have not. Bow is symmetric with respect to the line of aim. This part is named as grip (qabza) where archer grips the bow. The smooth bending part is the limb section. It is the working part of the bow. The kink part is kassan section. There are transition points between grip-limb and limb-kassan parts. They are named as grip eye (grip throat) and kassan eye, respectively. Bending occurs widely between these two points. Nock point is the attachment hole for fixing the string at the tip section. Grip, kassan and tip are rigid parts of the bow. These parts gain their rigidity particularly from their cross sectional shape (see Fig. 5). Bow has a rectangular cross section its width greater than its thickness starting from grip to kassan. However beginning from kassan, cross sections becomes thick until the tip part that assumes nearly a square cross section [9].

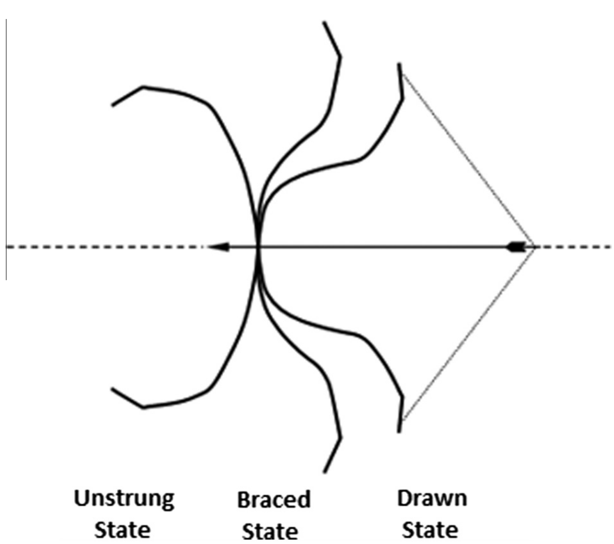

Fig. 1. The three states of a recurved bow.

2. Beam mechanics

Typical recurved bow in its drawn state is shown in Fig. 2. The key components in all bow types are the same. They are the draw length, the distance between qabza and nock point and the height at braced position. A rigorous mechanical model of the bow requires a precise definition of the basic geometrical features of

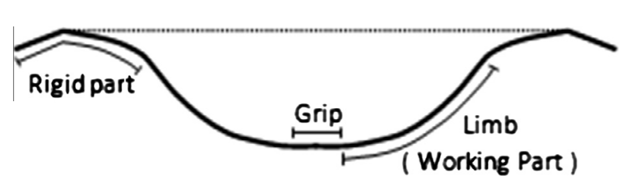

Fig. 4. The part of a recurved bow.

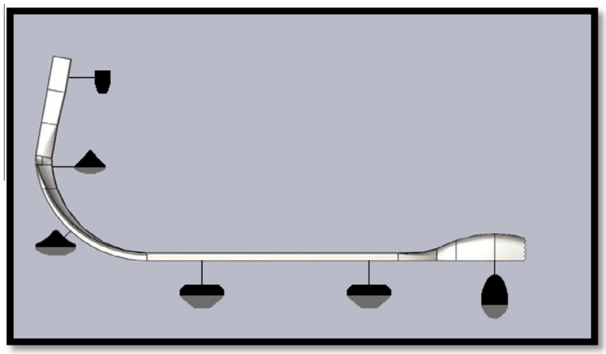

Fig. 5. The cross section of bow (lighter part are added later for embellishment).

the bow. Hickman developed a number of mechanical models [13]. The related studies, however, are not available in the open literature. He developed an analytical method to determine the dynamic force, the accelerations and velocities of the arrow. His mode was very simple. He treated the limbs as rigid elements connected to the grip by linear elastic hinges. Kooi and Bergman showed the characteristic performance of different bow types [14]. In their model, the limbs are treated as beams storing elastic energy due to bending. In a different study [5] Kooi used several linear elastic hinges connecting the rigid elements with their mass concentrated at the center. Kooi's results are validated for long bows. Since the profile of a recurved bow is basically different than that of long bows, the validation of the Kooi's analysis should be extended to required bows.

The Hungarian bow is a typical recurved bow. Since Turkish and Hungarian bows are very similar in shape, Horvath model as described in [17] can be extended to predict the behavior of Turkish bows. Horvath's analysis is based on a number of simplifying assumptions. Since kassan and tip parts of the bow are rigid, nearly no bending occurs at these sections. The limb itself is treated as an arc with uniform cross section. Neglecting the cross sectional variation along the limb arc in the Turkish, the analysis of Horvath is taken as valid for Turkish bow as well.

To investigate statics of the recurved type of bow three points on bow are defined. Point 1, point 2 and point 3 are end points of qabza, limb and kassan section respectively. As the bow is drawn point 2 and point 3 positions are chancing while point 1 is fix. The new point of the point 2 can be calculated by mechanics of material approach. Vertical and horizontal forces as well as momentum are calculated by deflection of curved member. The limb is accepted as a curve which is a flat curved member supported at one end. Thus the change in angle and displacement are calculated [15,16].

$$\varphi = \frac{r}{EI}(a_1M + a_2rF + a_3rH) \tag{1}$$

$$h = \frac{r^2}{EI}(b_1M + b_2rF + b_3rH) \tag{2}$$

$$v = \frac{r^2}{EI}(c_1M + c_2F + c_3rH) \tag{3}$$

$$a_1 = \beta$$

$$a_2 = c_1 = \beta\sin\beta - \beta\cos\beta$$

$$a_3 = b_1 = \beta\sin\beta + \beta\cos\beta - 1$$

$$b_2 = c_3 = 0,5 - [1,5\beta\sin\beta + \beta\cos\beta - 1]\cos\beta$$

$$b_3 = \beta[0,5 + \sin^2\beta] + (1,5\cos\beta - 2)]\sin\beta$$

$$c_2 = \beta[0,5 + \cos^2\beta] - 1,5\cos\beta\sin\beta$$

where φ is the angle between point 2 final and origin position, h and v are horizontal and vertical distance of this point respectively. The method of gradual approach is applied to reach acceptable error. When the transformation matrix and the new position of point are gained, last situation of point 3 can also be calculated. Draw weight is the maximum amount of force an archer will apply while drawing the bow. This maximum force is calculated by using the following equations:

$$F_x = \frac{F_1}{2\cos\gamma} \tag{4}$$

$$\cos\gamma = \frac{x - x_{s3}}{B} \tag{5}$$

$$x_{s3} = \frac{ab - \sqrt{a^2b^2 - (1+b^2)\cdot(a^2 - s_3^2)}}{1+b^2} \tag{6}$$

$$a = \frac{x^2 + (L-s_1)^2 + s_3^2 - B^2}{2(L-s_1)} \tag{7}$$

$$b = \frac{x}{L-s_1} \tag{8}$$

Here F_x is draw weight. γ is the angle between the string and horizontal plane. x_{s3} is the projected distance of s_3 on the base plane. The drawing force continuously increases while the bow is drawn. Starting with the braced state up to the drawn state, the geometry of the bow can be calculated iteratively. Iteration is stopped when error limit is reached. The force F_x acting on the arrow is a function of the angle between the string (γ) and the base line. At braced state the angle is perpendicular to the string. As the bow is drawn the angle decreases. In the Horvath's analysis, the imparted force to the arrow has found to vary linearly with draw length [17–19]. The comparison between the manufactured bow and mathematical model is shown in the further section.

2.1. Profile

Turkish bow is a recurved bow. The advantage of this type of bow is that at braced position initial force on the arrow is different than zero. The non-zero initial force is simply due to the initial tension of the string [18,19]. As compared to other types, for the same final draw weights, recurved bow with its reflex profile causes more energy to accumulate. The difference can be felt especially at the initial and mid-stage of the draw process.

This phenomenon can best be represented with a draw weight versus draw distance plot as shown in Fig. 3. The area under the draw weight – draw distance curve represents the accumulated energy in the bow. While conventional bows give a straight line, the Turkish bow gives a curve which is concave down. The area in between the two curves, as shown dashed in Fig. 3, gives the difference in the accumulated energy.

2.2. Bow parts

Grip is the stiff part and it is where the bow is handled (Fig. 4). In order to serve as a handle, it is manufactured as the thickest part of the bow. It has an elliptic section with trimmed bottom. Based on samples from museum collections, grip varies between 9 and 14 cm in length. Since it has no effect on the bow performance and arrow speed, traditional grip design is replicated without any

alteration. The important part of the grip is its eye where the arrow either on its right or left is supported while shooting. Grip eye has an offset with respect to the grip center by 6 to 8 cm. Offset depends on the size of the archer's hand.

Grip eye is the narrowest part of the bow. Theoretically, the propelling force acts along the line of aim. Due to the unavoidable width of the grip eye, arrow will have an offset from the line of aim equal to the half of the width. Due to this offset, the arrow will vibrate in the plane perpendicular to the bow plane and therefore, undulate in its motion toward the target. Due to the offset of the arrow with respect to the bow eye center, as the archer draws the bow, the bow will experience torsion, superimposed on in-plane bending. Such a combined loading is important issue in designing the composite structure.

Limb is the most important part of the bow. Probably the bow will fail at limb. Traditional Turkish composite bow has a sandwich structure in which organic materials are used. As the bow is drawn, the archer side and the side opposite to the archer act differently. While the archer side is in compression, the opposite side is in tension. It is for this reason that traditional bows are reinforced by sinew on their side opposite to the archer and by horn on their archer side.

The geometry of the limb cross section is influential on the bow efficiency. Since a half round section has always less area as compared to that of a rectangular section, a half round section is preferred for the limb section. A half round section allows using less material for optimum design. Such a section will reduce the material usage approximately by 30% [4].

3. Manufacturing

Using the compiled geometric data from the museum collections and the literature, a bow is designed using the ANSYS Design Modeller [20]. A mold suitable for hand lay-up is designed and manufactured. The mold basically consists of two parts which are the mirror images of each other. E-glass fiber cloth cut in appropriate shape is laminated within the mold cavity using epoxy resin [21]. For strength purposes, continuous fibers are laid along the bow length with higher fiber density in narrower sections. Narrow sections are thus strengthen. Since bow thickness varies from tip to tip, more fiber is laid in thicker sections. The bow at its grip throat is further reinforced by skew-symmetric 60° fibers to eliminate twisting. The entire mold with fibers laid in epoxy is packed in a plastic bag and vacuumed as shown Fig. 6. The epoxy is allowed to cure for twenty-four hours at room temperature. Cured structure taken out of the mold in ready for use.

The bow was calibrated and its draw weight is determined. The calibration setup consists of a fixture fixing the bow. The drawn force at different draw distances was measured with a spring balance. The calibration curve is given in Fig. 7. Standard draw distance for a typical Turkish bow is 70 cm (28 in.). This distance is measured from outer face of the qabza to the string. At this draw distance measured draw weight was 29,5 kg (65 lb). The draw weight – draw distance characteristic of the bow is found to be in congruence with that of similar traditional bows and that of simulated bows. From beginning of the draw, up to approximate half the draw distance, draw weight increases with the square of the draw distance from the mid draw position onward draw weight varies linearly with draw distance. The natural consequence of this recurved bow characteristic is that more effort is required to draw such bows as compared to non-recurved bows.

Fig. 6. The vacuum packed mold.

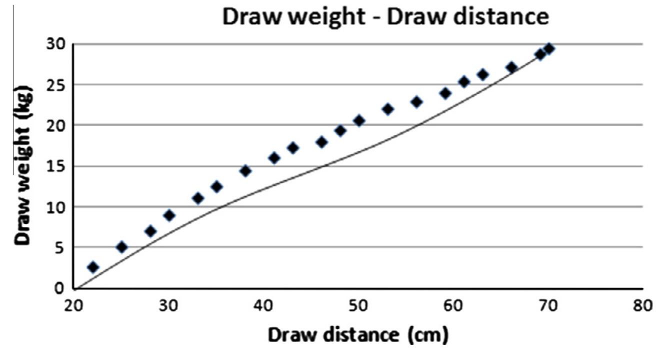

Fig. 7. Draw weight – draw distance of the manufactured bow and calculated bow.

Mathematical model is very close to linear relationship. However as mentioned before recurved type of bows have concave path on draw weight – draw distance graph. At the preliminary section we had assumptions. One of the was limb has perfect arc shape, but simulation study and mechanical drawing show that bow has not perfect arc shape when drawing. This can cause difference between calculated and measured forces. A correction factor may be applied. Also beam was assumed to be uniform cross-section, but in reality it is not. This is a second affect on the difference.

4. Optimization

An archery bow is evaluated in terms of its arrow speed, hit accuracy, draw comfort and controlled release and durability. Present study aims at to reduce the mass in the limb section in order to maximize the initial arrow velocity and therefore to boost the efficiency. Deformation in the draw direction under static load, plastic strain and equivalent stress are taken as the restrictions.

Self bows consisting of a single material are bows which are manufactured easily with no production subtlety. Curvature of such bows is not appreciable and they are powerful only if they are long. They can be as high as a human. English bows, known as long English bows, are such typical bows compared to recurved bows, the effective range of long bow is necessarily less. Due to their heavy limbs they result in lower initial arrow speed. Moreover, due to their length, they cannot be used while horse riding. Recurved bow design requires highly elastic behavior, especially in the limb section. As the bow is drawn, the limb acts as a cantilever with compression on its belly and tension on its ridge. It is difficult to find a single material that will provide sufficient strength under high degrees of both tension and compression. Composites provide good solutions in such demanding applications [22,23]. In early traditional bows organic composites are used. Sinew is used as the fiber in the composite. Fish glue is used as resin. In today bows organic composites are replaced by modern composites in cooperating carbon, aramid or E-glass fiber. Epoxy is the common resin in such applications [22,23].

The higher the draw weight, the higher the initial speed will be. Higher draw weight can be achieved with high level of reflex and therefore a recurved profile with higher curvature. Draw weight can also be increased by thickening bow thickness. While draw weight can be increased by increasing the reflex level or by

increasing the bow thickness, increase in draw weight is limited with archer's potential. Therefore, bow designs with high reflex or thicken should not be aimed at. The aim should be to achieve high efficiency bows giving higher initial speeds with lower draw weights. The main concern of the present study is to develop bows of this nature.

Basically, bows store energy and impart the stored energy to the loaded arrow. As such, performance of a bow is characterized by its ability to store energy. If the draw force F is applied at a distance x, the stored elastic energy can be computed as:

$$E = \int_{x=0}^{x=D} F(x)dx, \tag{9}$$

where D is the maximum draw distance. For an arrow of mass m, the kinetic energy imparted to the arrow will be:

$$K = \frac{1}{2}mV^2 \tag{10}$$

where V is the initial arrow velocity.

The efficiency of the bow is then defined as the ratio of the kinetic energy imparted to the arrow to the stored elastic energy. Fundamental parameters affecting the bow efficiency are the mass of limb with rigid section and the mass of the arrow. As the archer releases the string, the arrow is propelled and the limb is set into vibration. As such, the limb consumes part of the stored energy and thus allows only part of the stored energy to be imparted to the arrow. Our aim is to increase the bow efficiency by reducing the energy consumed by the limb.

4.1. Optimization of the design

Parametric optimization is crucial in the design process. It reduces both the development time and cost. There are many optimization tools. In this study ANSYS® mechanical APDL is used. For small number of optimization parameters mechanical APDL is a highly efficient tool [24,25].

Based on the complied data, the bow is drawn in the ANSYS Workbench design modeler considering the weak sections with their beginning and end points [26,27]. Parameters governing the behavior of the bow are first identified. These parameters are sufficient to identify the bow geometry and its design.

To avoid failures in the regeneration of the model in the iteration process, mathematical relations between parameters were defined. Since the bow is symmetric both in the y-direction (longitudinal direction) and in the z-direction (lateral direction), only one quarter of the bow is modeled as shown in Fig. 8.

Table 1
Data of reinforced with glass fiber resin static test in standard climate.

Data of reinforced with glass fiber resin static tests in standard climate Hexion L285 epoxy (%45 fiber)		
Flexural strength	[N/mm^2]	510–560
Tensile strength	[N/mm^2]	460–500
Compressive strength	[N/mm^2]	410–440
Modulus of elasticity	[kN/mm^2]	20–24

Optimization is the process of identifying the optimum solution among a set of candidate solutions. Basically it involves either the maximization or minimization of an objective function in the presence of constraints. The solution domain is defined through optimization parameters. Glass fiber reinforced epoxy is used to construct the bow. Material property data for this composite is given in Table 1.

The first step of the optimization process is to create a 3-D solid model of the bow. The model is characterized in terms of seventeen parameters which are summarized in Fig. 9. The bow is fixed at its grip part. The bow is loaded with a standard draw weight of 31.9 kg (70 lb). Since the sections of the bow ahead of the nock point and the upper part of the grip section have no effect on the bow performance, these parts are not included in the model. Deflection in the limbs is excessive.

Therefore the model allows for geometric non-linearity. Static strain analysis of the bow was done within the ANSYS Workbench environment. Equivalent strain results are given in Fig. 10. In contrast with the earlier fundamentals assumption that limb deforms into a circular arc [17], limb deflection is noncircular and complex in nature. The maximum stress occurs at the grip eye. Although stress is maximum at the grip eye, it remains within safe limits.

The range of each parameter in the parameter set that characterizes the bow design is given in Table 2. Base on these parameters, experiment design results in 291 design points. At each design point, finite element structural analysis of the bow is carried out to obtain the set of performance parameters characterizing behavior of the bow at that point. The set of performance parameters consists of the maximum deformation in the transverse direction, namely the x-direction, the maximum equivalent stress and the strain energy. These parameters are generally referred to as the output parameters.

Based on the solutions at these design points, the local sensitivity chart and the response surfaces are obtained. The local sensitivity chart shows the impact of the input parameters on the output parameters. A typical sensitivity chart is shown in Fig. 11. A response surface gives the variation of output parameters over

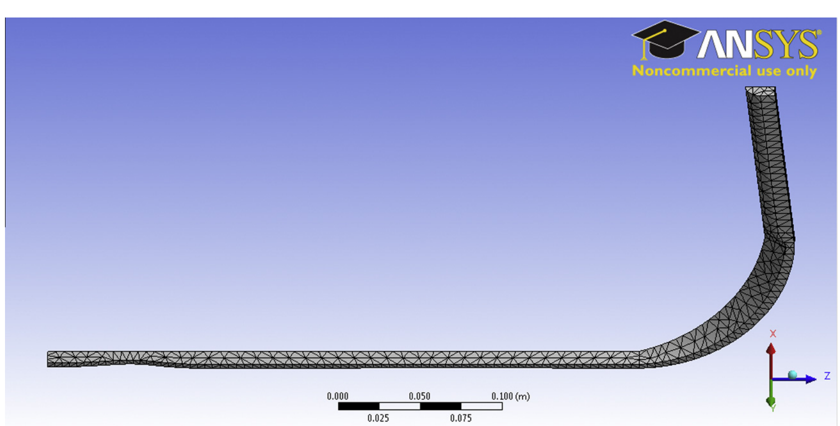

Fig. 8. Finite element modeling; symmetric model.

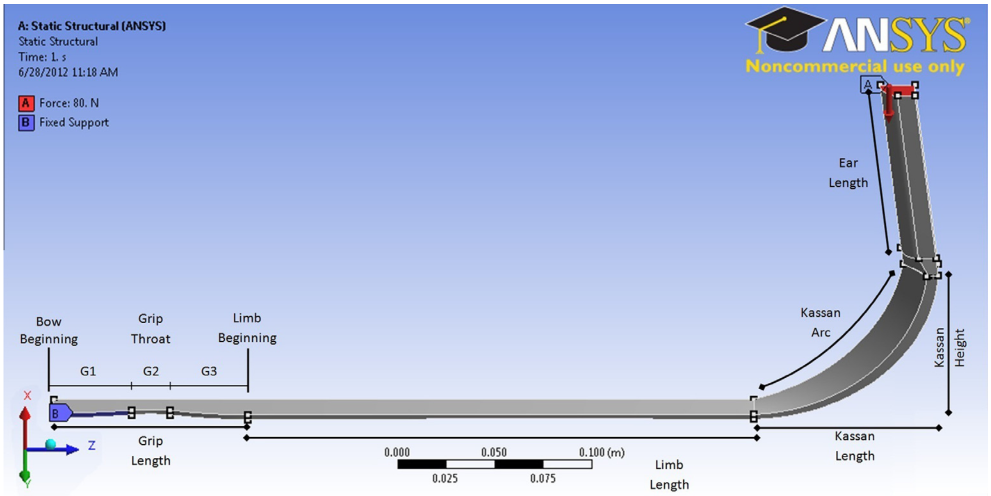

Fig. 9. The parameters of the bow.

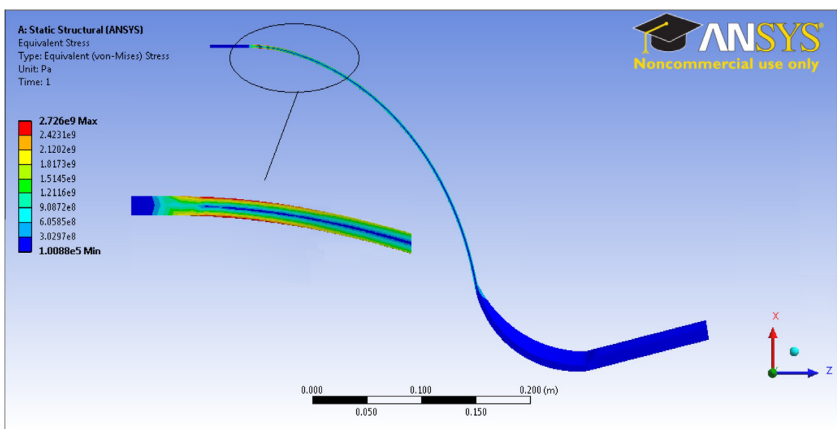

Fig. 10. The simulation result of the bow.

the search domain, the domain designed by the input parameters. The response surface is basically created via a curve fit through the design points. From the response surface it will be possible to find out output results for input parameter combination that has not been solved for.

As it can be seen in Fig. 11, the most influential input parameter on all the output parameters is the thickness. The effect of thickness on the transverse deformation is 6 times larger than the effect of kassan width which is the next influential parameters affecting the transverse deformation. The effect of thickness on strain and, therefore, stored energy is appreciable as well. Since organic composites offer less strength, older bows were thick. With new composites, although the same strength can be achieved with thinner sections, such bows will be more compliant and capable of storing less energy. As important as stored energy, susceptibility to twist is crucial. Since these bows can twist, bows with thickness less then 5 mm should be avoided. Such bows necessarily require higher draw weights. Increased draw weight with increasing thickness should then be reduced by controlling parameters such.

The other parameters that are effective are the parameters related to the kassan and the limb. The effect of parameters related to the tip part is low and, therefore, can be neglected. Since the grip is fixed, its effect on transverse deformation, and strain energy can effectively be ignored.

An optimum design may end up with highly stress in the bow. The stress level may approach the maximum possible strain.

Table 2
The parameters and their ranges.

Parameters		Range (mm)
P1	Kassan cutting	2.5–3.0
P2	Kassan arc	100–120
P3	Kassan height	90–105
P4	Kassan width	100–120
P5	Kassan end	16.2–19.8
P6	Thickness	4.5–7.0
P7	Grip eye	9.0–10.0
P8	Bow beginning	11.5–13
P9	Grip 1	36–44
P10	Grip 2	18–22
P11	Grip 3	36–44
P12	Limb end	12.0–14
P13	Limb length	240–280
P14	Limb beginning	13–15
P15	Tip width	9.0–10
P16	Tip thickness	18–20
P17	Tip height	94.5–115.5

Parameters controlling the stress are that of the kassan, limb and the thickness itself. While it is possible to control the stress by increasing the thickness, increase in thickness is associated with an important adverse effect. With increasing thickness, draw weight also increases which is not desirable. Although the influence of the grip eye on bow performance seems to be negligible

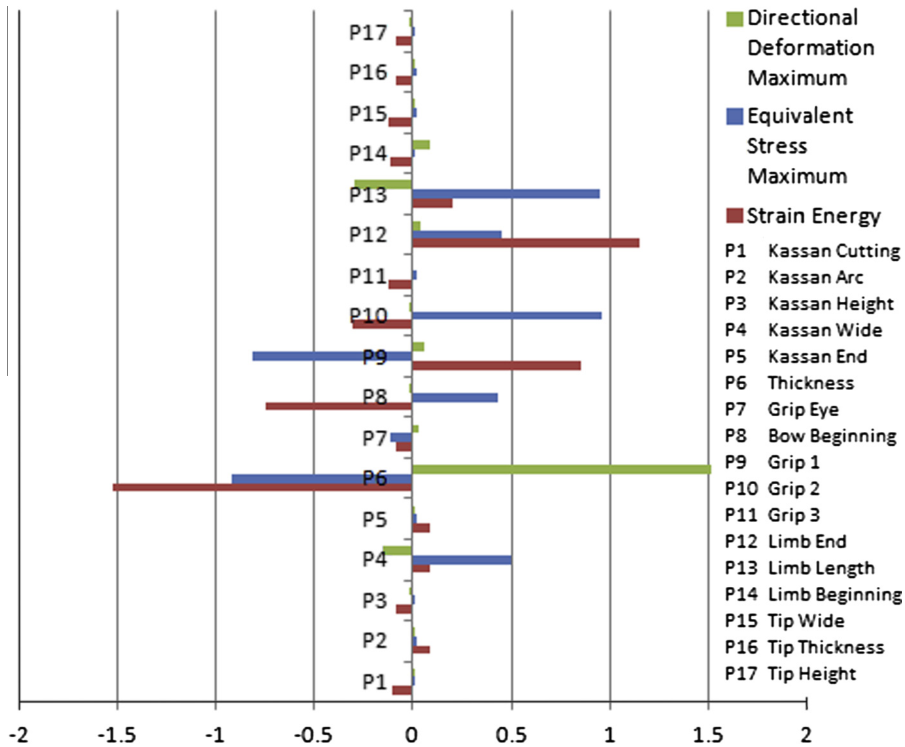

Fig. 11. The local sensitivity chart of the bow.

from the durability point of view it should not be ignored since it is the narrowest section in the bow.

The effect of the design parameters on the output parameters are easily observed in the graphs for the response surfaces. Such typical surfaces are shown in Fig. 12. Fig. 12(a) shows the variation of maximum equivalent stress as a function of kassan width and kassan arc. Fig. 12(b), on the other hand, shows the variation of maximum equivalent stress as a function of thickness and limb length. Maximum equivalent stress first increases, goes through a maximum and then decreases, as kassan width increases. The variation of maximum equivalent stress with kassan arc is similar: first it increases, goes through maximum and decreases. As it can be seen from the graph maximum equivalent stress occurs approximately at the mid value of the kassan width and kassan arc, which is typically 110 mm. From this behavior, one can conclude that if kassan width is to take its mid range value, the kassan arc cannot take its mid range value and vice versa.

As expected, maximum value of the stress is inversely proportional to its thickness. For a safe bow, bow thickness should not be lower than 5 mm. Fig. 12 shows that limb length has no appreciable effect on stress. Limb length, on the other hand, is detrimental for the bow mass and, therefore, affecting the bow efficiency.

Once the response surfaces are obtained, the optimum design can be achieved through goal driven optimization. In goal driven optimization, design parameters are associated with corresponding weight and either declared to be minimized or maximized.

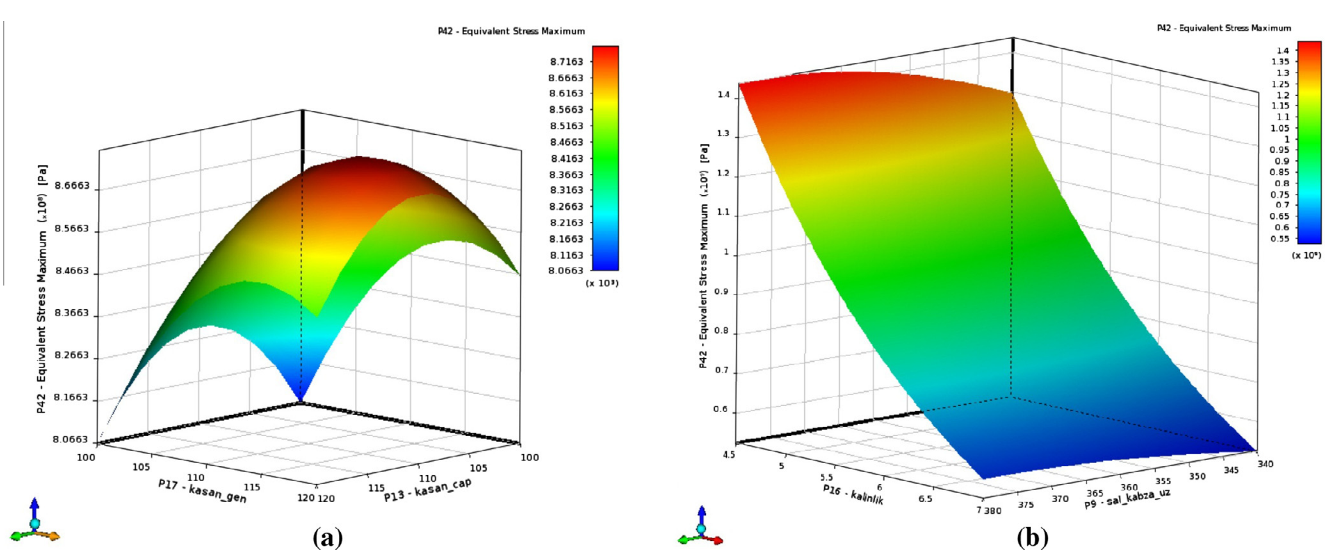

Fig. 12. The response surfaces for kassan width, kassan arc and limb, thickness with respect to maximum stress.

Table 3
The initial design and optimum design results and their differences.

Parameters		Initial design (mm)	Optimized design (mm)	Difference (%)
P1	Kassan cutting	2.5	2.78	11.2
P2	Kassan arc	110	103.2	−6.2
P3	Kassan height	90	102.2	13.6
P4	Kassan length	110	105.8	−3.8
P5	Kassan end (width)	18	17.8	−1.1
P6	Thickness	6	5.2	−13.3
P7	Grip eye (width)	9	9.1	1.1
P8	Bow beginning (width)	13	12.8	−1.5
P9	Grip 1 (G1)	40	38	−5
P10	Grip 2 (G2)	20	21.3	6.5
P11	Grip 3 (G3)	40	42.4	6
P12	Limb end (width)	13	13.1	0.8
P13	Limb length	260	261.4	0.5
P14	Limb beginning (width)	13	14.5	11.5
P15	Tip width	9	9.6	6.7
P16	Tip thickness	18	19.7	9.4
P17	Tip height	105	111.4	6.1
O1	Equivalent stress max. (MPa)	2700	2250	−16.6
O2	Geometrical mass (Gr.)	560	480	−14.2

The basic step of the goal driven optimization scheme is outlined below:

1. Define design goals for the optimization.
2. Create new design points through sample generation from the specified goals.
3. Select the best candidate or candidates and verify the validity of the candidate design point by analyzing the finite element platform. This will complete the generation of the set of reference design points.

In goal driven optimization methodology Screening, Moga and NLPQL options are available. Screeing is preferred in the present study. While screeing a new sample set is generated and the sample are sorted based on the set objectives. Directional deformation and strain energy are maximized while the geometric mass is minimized. Mass and equivalent stress are declared to have higher importance. Upon updating goal driven optimization, rated candidate designs are obtained. The design with the highest rating is then selected. The initial design prior to optimization and the optimum design are compared in Table 3.

The initial and the optimized designs are compared in Table 3. The comparison reveals that there are no drastic difference between the original a design and the optimum design. As a result of the optimization, there is an increase in some parameters as well as a decrease in other parameters. As a whole, however, there appears no appreciable improvement. This can be attributed to the fact that the original design is a strict replica of museum samples. These bows are inherently optimum in the sense that they reflect the improvements based on usage over a time span consisting of several centuries.

Draw weight of the curve was calculated by Horvarths' formula ($2S_1 = 120$ mm, $S_3 = 110$ mm, $2L = 1200$ mm, $A = 95$ mm, $B = 380$ mm, $X = 180$ mm). It is 29.16 kg (64.38 lb). There is 2.6 kg difference. In this model there were two assumptions which are limb makes perfect arc and cross section is same along bow. Simulation studies showed that limb does not make a perfect arc. Therefore it can be said that recurve shape cause this difference. Since cross-section of the Turkish bow is variable along bow, draw weight expected to be lower.

5. Conclusion

In spite of the fact that the Turkish bow is one of the best bows, its performance and mechanical properties have not been documented in detail. The preliminary design of the bow studied in this work is, therefore, based on geometrical and structural data gathered from the museum collections in Turkey. The preliminary design is optimized for maximum performance. To this end a computer integrated optimization scheme is employed. The entire optimization process is fully automatic and streamlined.

The superiority of the Turkish bow as compared to others can be attributed to its unique structure defined by its recurved profile and distributed rigidity. The recurved profile allows for higher energy storage. The bow is not uniform rigidity throughout – it is rigid wherever it is required. For example while the grip and kassan-tip of the bow is designed to be rigid, the limb is designed to be compliant. The limb then acts as a cantilever beam and simulation result have proved that highest stress occurs at the grip throat.

A bow is manufacture and tested. The draw weight – draw distance characteristic of the preliminary bow is seen to agree with the characteristics of the traditional bow. At early and mid draw distance the Turkish bow requires more force as compared to other bows. Consequently it is capable of storing more energy and thus resulting in higher initial arrow speeds.

The mathematical model solutions and mechanical test measurements were compared. It is found that they are very close to each other but have small differences. There are probably caused by the assumptions that made in the preliminary section to make calculation easier.

The most important feature of a bow is its higher initial speed for the same draw weight. One way to granting a high initial speed capability for a given draw weight is to increase the bow efficiency by reducing the limb weight. A bow optimized for reduced mass will then serve for this purpose.

A typical bow is characterized in terms of seventeen parameters and the optimum design is searched for on the basis of response surfaces. The bow thickness is found to be the controlling parameter of this optimization process. Although the effect of bow thickness is detrimental, there exist additional geometric constraints. Bow thickness, for example, cannot be less than five mm since thickness lower than this are susceptible to twisting. Higher thicknesses, on the other hand, are not desirable since they require unreasonable draw weights, typically over 45 kg (100 lb).

Goal driven optimization points to different rated design. The one with the minimum equivalent stress at grip throat is identified as the optimum design. The optimum design does not exhibit appreciable differences from initial design. The change in the parameters characterizing the design is limited approximately

10%. This can be attributed to the fact that the original design is a strict replica of museum samples.

References

[1] Klopsteg PE. Turkish archery and the composite bow. Manchester (England): Simon Archery Foundation; 1987.
[2] Ozveri M. Okculuk hakkında merak ettiğiniz her şey. Istanbul (Türkiye): Private Publication; 2006.
[3] Alley SB, Comstock T, Hamm P, Hardcastle J, Massey R, Strunk J. The traditional bowyer's bible. Volume one, Canada; 1992.
[4] Karpowicz A. Ottoman Turkish bows: manufacture and design. Canada: Library and Archives Canada Cataloguing in Publication; 2008.
[5] Kooi BW. The design of the bow. Koninklije Nederlandse Akademie van Wetenschappen, Netherland 1994;97(3):1–27.
[6] Kooi BW. On the mechanics of some replica bows. J Soc Archer-Antiquaries 1993;36:14–8.
[7] Kooi BW, Sparenberg JA. On the static deformation of a bow. J Eng Math 1980;14(1):27–45.
[8] Timo A. Niemien. The Asian war bow. In: 19th Australian Institute of Physics Congress, ACOFTAOS; 2010.
[9] Demir S, Kentli A, Ekici B. Design and shape optimization of a Turkish Tirkeş bow. In: 1st International Symposium & 10th Balkan Conference on Operational Research, September 22–25; 2011. Thessaloniki Greece.
[10] Stemmler YE. The essentials of archery. New York: Manorville LI; 1942.
[11] Pagitz M, Bletzinger KU. Shape optimization of a bow. Struct Multidisc Optim 2004;28:73–6.
[12] Kooi BW. On the mechanics of the bow and arrow. PhD thesis, Rijksuniversiteit Groningen; 1983.
[13] Marlow WC. Bow and arrow dynamics. American association of physics teachers. Am J Phys 1981;49(4).
[14] Kooi BW, Bergman CA. An approach to the study of ancient archery using mathematical modelling. Antiquity 1997;71(271):124–34.
[15] Muttnyanszky Adam: Szilardsagtan. Muszaki Konyvkiado, Budapest; 1981.
[16] Hibbeler RC. Mechanics of materials 2006.
[17] Horvath S, Kortvelyesi G, Legeza L. The statics of the traditional hungarian composite reflex bow. Acta Polytech Hungari 2006;3(2).
[18] Amandeep S, Summerscales J, Hall W, Grove SM, Miles ME. Design, manufacture, mechanical testing and numerical modeling of an asymmetric composite crossbow limb. Composites: Part B 2009;40:249–57.
[19] Beer Ferdinand P, Russell Johnston E, Dewolf John T. Mechanics of materials. McGraw Hill; 2005.
[20] Liu S, Boyle M. Engineering design: perspectives, challenges, and recent advances. J Eng Des 2009;20(1):7–19.
[21] Hepworth DG, Smith JP. The mechanical properties of composites manufactured from tendon fibres and pearl glue. Composites: Part A 2002;33:797–803.
[22] Subic A. Materials in sports equipment, vol. 2. Cambridge: Woodhead Publishing; 2007.
[23] Grant A. Sporting composites. Reinforced Plast 2005;49(5):46–9.
[24] Egerland M, Roos D, Will J. Optimization of a fan shroud by ANSYS/Design Modeler and OptiSLang. In: ANSYS conference & 25th CADFEM Users' Meeting; 2007.
[25] Sancaktar E, Gratton M. Design, analysis and optimization of composite leaf springs for light vehicle application. Compos Struct 1999;44(2–3):195–204.
[26] ANSYS, 2008. Ansys theory reference manual. Release 8.0 Ansys Inc.
[27] Edelmann J, Heller M, Clement S, Vajna S, Jordan A. Lightweight design optimization of a bow riser in Olympic archery applying evolutionary computing. Euro J Sports Sci 2005;4(3):33–51.